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SUPERCAPACITOR BASE ON ACTIVE CARBON ELECTRODE: REVIEW

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Abstract— Supercapacitors are a promising technology in meeting the demands of electrical energy storage devices in the future. Active carbon-based supercapacitor electrodes provide high energy and energy performance due to their high surface area, high conductivity, and the ability to enable activated carbon to optimize the properties of their supercapacitors. This paper also reports on the manufacture of supercapacitors by utilizing activated carbon from various biomass as electrode material and the performance of supercapacitors compared to batteries. The activation method, type of activator, type of electrolyte, carbonation or pyrolysis process used will determine the energy and density of energy produced by supercapacitors. In this case the process of forming an electric double layer on the surface of the electrode was also reviewed and the effect of the type of electrolyte used on the performance of supercapacitors. The use of organic electrolytes can actually improve the performance of supercapacitors but in terms of ecology the use of acetonitrile solvents is not good for the environment. In this paper we recommend the simplest and lowest-cost fabrication technology but have more performance than the technology of poets such as lithium and alkaline batteries.

Keywords— activation, electrolytes, activated carbon, capacitance, supercapacitor

I. INTRODUCTION

One of the challenges faced in the future is the problem of energy storage. Important considerations for the use of renewable, environmentally friendly and easily found energy storage systems, including responding to the ecological concerns that arise from modern society [1]. Supercapacitors as an alternative technology for energy storage devices with very high capacity and low internal resistance. Supercapacitors are also capable of storing and sending energy at a relatively higher rate compared to batteries because of the energy storage mechanism that involves the separation of charge and ions at the interface between the electrodes and electrolytes [2,3]. Some of the advantages of supercapacitors when compared to other energy storage devices include durable, high power, flexible packaging, a wide thermal range (-40°C to 70°C), low maintenance costs and light weight [4].

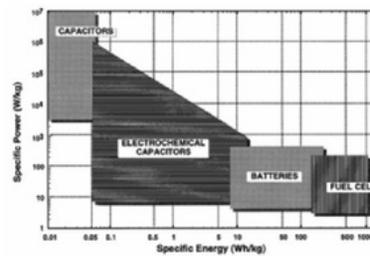


Figure 1.1 - Ragone plot of various energy storage devices.

As can be seen in Figure 1-1, supercapacitors are between conventional batteries and conventional capacitors. The battery has a slight decrease when used to high power, and conventional capacitors cannot be used due to lack of energy. Supercapacitors offer high power density along with adequate energy density for most short-term high-power applications. Many users compare supercapacitors with other energy storage devices including conventional batteries and capacitor technology. Each product has its own advantages and disadvantages compared to other technologies as can be seen from the table 1 below.

TABLE I. ADVANTAGES AND DISADVANTAGES BATTERY, SUPERCAPACITOR AND CONVENTIONAL CAPACITOR

Available Performance	Lead Acid Battery	Supercapacitor	Conventional Capacitor
Charge Time	1 to 5 hrs	0.3 to 30 s	10^{-3} to 10^{-6} s
Discharge Time	0.3 to 3 hrs	0.3 to 30 s	10^{-3} to 10^{-6} s
Energy (Wh/kg)	10 to 100	1 to 10	<0.1
Cycle Life	1000	>500,000	>500,000
Specific Power (W/kg)	<1000	<10,000	<100,000
Charge/ Discharge efficiency	0.7 to 0.85	0.85 to 0.98	>0.95
Operating Temperature	-20 to 100°C	-40 to 65°C	-20 to 65°C

In addition to bridging the gap between conventional capacitors and batteries, supercapacitors also have several advantages that are desirable to make an attractive energy storage option. The supercapacitors mechanism in storing

and releasing loads is completely reversible, so it is very efficient and can have a large cycle of filling/emptying. They can store or release energy very quickly, and can operate at various temperatures.

Therefore, the aim of this thesis is to present a complete review of supercapacitor technology with the aim of fostering better understanding in the engineering community. The contents of this thesis are intended to be used by electrical engineering practitioners or engineering students who want to get a lot of information about this new technology.

A. Historical Background

Electric storage at the interface between metal and electrolytic solutions has been studied by chemists since the nineteenth century, but the practical use of new supercapacitors began in 1957, when General Electric obtained patents for electrolytic capacitors using porous carbon electrodes [5]. Then, in 1966, The Standard Oil Company, Cleveland, Ohio (SOHIO) patented a device that stores energy in a double layer interface [6]. At the moment SOHIO recognizes that multiple layers at the interface behave like capacitors with relatively high specific capacities. SOHIO then patented disc-shaped capacitors in 1970 using carbon pastes soaked in electrolytes [7]. In 1971, due to reduced sales, SOHIO abandoned further development and licensed the technology to NEC (Nippon Electric Company) [8]. NEC continued the production of the first commercially successful double-layer capacitor under the name "supercapacitor".

In the 1980s a number of companies produced supercapacitors. Matsushita Electric Industrial Co., has developed "Gold capacitors" since 1978. As produced by NEC, this device is also intended for use in memory backup applications [9]. In 1987 ELNA began producing their own supercapacitors under the name "Dynacap" [10]. High-power supercapacitors were first developed by the PRI (Pinnacle Research Institute). "PRI Ultracapacitor" was developed since 1982, incorporates metal oxide electrodes and is designed for military applications such as laser weaponry and missile guidance systems [11]. News of this device triggered a study by the United States Department of Energy (DoE) in the context of hybrid electric vehicles, and in 1992 the Development Program for DoE Ultracapacitor was underway at Maxwell Laboratories [12].

B. Current Research

Research is currently being carried out in a number of institutions to increase the energy density and technological power of supercapacitors. Activated carbon is the most commonly used electrode material in commercial supercapacitors, and many researchers are interested in factors that contribute to specific capacitance and series resistance to these materials. Université Henri Poincaré-Nancy in France has conducted research on the correlation between the structure of porous electrode and series resistance [13]. Other research conducted by the French laboratory at the Conservatoire National de Arts et Métiers found the impact of pore size distribution on specific capacitance [14].

Nanotubular carbon has been explored recently by a number of academic institutions such as Poznan University

of Technology, Poland, and Sungkyunkwan University in Korea have built electrodes that show higher specific capacitance than those achieved by activated carbon [15, 16]. Research at the Chinese Academy of Science has investigated further and showed that activated carbon nanotubes have a higher specific capacitance than normal carbon nanotubes [17]. Considerable interest has also been shown in conducting polymeric materials, and research shows that high specific capacitance can be achieved [18].

The most promising results are shown in the use of hybrid configurations, which consist of activated carbon and conduction polymers or metal-oxides. Study at the University of Bologna, Italy has produced supercapacitors that have positive activated carbon electrodes and negative polymer electrodes that outperform those using only activated carbon [19]. Research at National Cheng Kung University in Taiwan shows that high specific capacitance can be achieved by deposition of conduction polymers into activated carbon [20]. Frackowiak et al. at the University of Poznan Technology has shown an increase in the specific capacitance of carbon nanotubes coated with polymers [21]. Also interesting is the study of solid-state supercapacitors conducted at the University of Twente in the Netherlands, where yttria-stable zirconia is used instead of liquid electrolytes [22].

C. Future Research

Active carbon currently dominates the market as an electrode material, but progress in the development of conduction polymers and metal oxides continues. Exploitation of the pseudocapacitive effect to increase the capacitance of supercapacitors seems to be a goal among researchers today, and offers a good opportunity to develop generations of supercapacitors that have high capacitance and high energy.

II. PRINCIPLES OF SCIENTIFIC BASIC

Electrochemical capacitors operate on a principle similar to conventional capacitors. Conventional capacitors store energy in the form of an electric charge, and this device generally consists of two conduction materials separated by a dielectric (Figure 2.1).

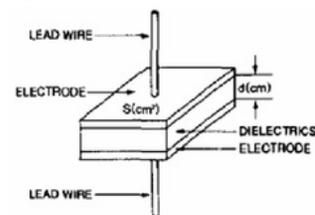


Figure 2.1 - Electrostatic capacitor topology [23].

When an electric potential is applied across a conductor, electrons begin to flow and the charge accumulates in each conductor. When potential is released, the conductor plate remains charged until they are connected again, so that energy is released. The amount of charge that can be stored is related to the potential strength applied which is known as capacitance, and is a measure of the capacitor's energy

storage capability. Equations 2.1 and 2.2 apply to conventional capacitors.

$$C = \frac{Q}{V} = \epsilon \frac{A}{d} \quad (2.1)$$

$$U = \frac{1}{2} CV^2 = \frac{1}{2} QV \quad (2.2)$$

Where C is the capacitance in Farad, the charge Q in Coulombs, V is the electric potential in Volts, ϵ is the dielectric constant of the dielectric, A is the surface area of the conductor, d is the dielectric thickness, and U is potential energy.

Supercapacitors store electrical charges in the same way, but the charge does not accumulate on two conductors separated by a dielectric. The load will accumulate at the interface between the surface of the conductor and the electrolyte solution (Figure 2.2).

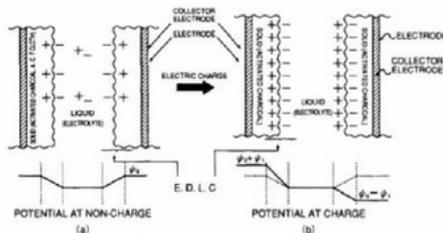


Figure 2.2 - Supercapacitor load storage mechanism [23]

Accumulation of charge will form a double layer of electricity, the separation of each layer is in the order of several Angstroms. Estimates of capacitance can be obtained from the multiple-layer model proposed by Helmholtz in 1853, where the double layer consisted of two layers of charges. One layer is formed on a filled electrode, and the other layer consists of ions in the electrolyte. Specific double layer capacitance given by Equation 2.3.

$$\frac{C}{A} = \frac{\epsilon}{4\pi\delta} \quad (2.3)$$

Where C is the capacitance, A is the surface area, ϵ is the relative dielectric constant of the medium between two layers (electrolyte), and d is the distance between two layers (distance from the surface electrode to the center of the ion layer) [10-8]. This estimate is true for concentrated electrolyte solutions.

The supercapacitor device consists of two electrodes that allow potential to be applied in the cell, so that there are two double layers, at each electrode and electrolyte interface. Permeable ion separators are placed between the electrodes to prevent electrical contact, but still allow ions from the electrolyte to pass through (Figure 2.3). Electrodes are made of large effective large surface materials such as porous carbon or carbon aerogels to maximize the surface area of the double layer. Therefore a high energy density can be achieved in supercapacitors because the high specific capacitance is obtained due to the high surface area of the electrode and electrolyte and the separation of the charge layer is very small on the atomic dimension.

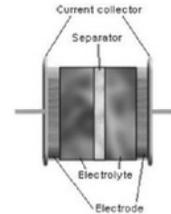


Figure 2.3 - Conceptual diagram of construction of supercapacitors.

In addition to capacitance arising from the separation of charges in a double layer, contributions to capacitance can be made from reactions that can occur at the electrode surface. The charge needed for the occurrence of these reactions depends on the potential, resulting in Faradaic 'pseudocapacitance'.

A. Electric Double Layer

An understanding of the electrical processes that occur at the boundary between solid conductors and electrolytes has developed. Various models have been developed over the years to explain the phenomena observed by chemical scientists.

When Helmholtz first revealed the term "double layer" in 1853, he imagined two layers of charge at the interface between two different metals. Then, in 1879, he compared this metal and metal interface with the metal interface and electrolyte solution [24]. In this model, the interface consists of layers of electrons on the surface of the electrode, and a single layer of ions in the electrolyte.

In the early 1900s, Gouy assumed that capacitance was not constant depending on the potential applied and ion concentration. To explain this behavior, Gouy proposed that thermal motions retain ions from the accumulation at the electrode surface, instead forming a charge of the diffusion chamber. To formulate this model Poisson equations are used to connect potential to fill density, and the Boltzmann equation is used to determine ion distribution. Ions are considered as point charges without volume. This model is also done by DC Chapman, and is currently called the Gouy-Chapman model.

In 1924, Stern modified the Gouy-Chapman model by incorporating a compact layer and a Gouy diffusion layer. The compact Stern layer consists of a layer of ions specifically adsorbed [25]. Grahame divides the Stern layer into two regions. He stated the closest approach of ion diffusion to the electrode surface as the outer Helmholtz field. The ion layer adsorbed on the electrode surface is specified as the inner Helmholtz field.

This model apparently has not improved significantly in formulation, because any capacitive effects that might result from a dipole will interact with the surface of the electrode charged not considered in this model.

In 1963 Bockris, Devanathan and Muller proposed a model that included the action of solvents [25]. They suggested that a layer of water be present in the Helmholtz inner field on the surface of the electrode. Dipoles from these molecules will have a fixed alignment because of the charge in the electrode. Some water molecules will be moved by

ions specifically adsorbed. Another layer of water will follow the first one, but the dipole in this layer will not remain as in the first layer (Figure 2.4).

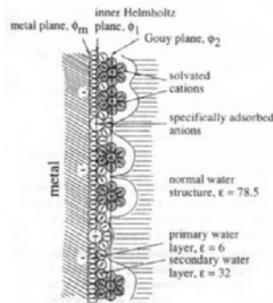


Figure 2.4 - Double layer models including solvent layers [25].

B. Pseudocapacitance

Pseudocapacitance arises from a reversible Faradaic reaction that occurs at the electrode, and is represented as 'false' capacitance to distinguish it from electrostatic capacitance. The transfer of charge that occurs in this reaction depends on the voltage, resulting in a capacitive phenomenon.

Pseudocapacitance redox in Ruthenium-oxide was studied at the University of Ottawa, Canada. In Figure 2.5, the voltage/current characteristics indicate the reversible nature of the Faradaic redox reaction. The charge/discharge curve is also the result of overlapping redox reactions as significant double layer capacitance due to the porous structure of hydroxide [26-26].

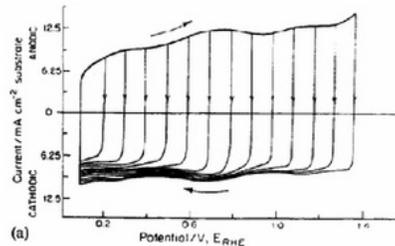


Figure 2.5 - Cyclic voltammogram of the ruthenium-oxide electrode in sulfuric acid electrolytes [26].

III. CAPACITOR CONSTRUCTION

Various types of materials, construction and process of supercapacitors affect various aspects of each alternative which can have a significant impact on device performance.

A. Electrode Materials

The selection of electrode materials has an important role in determining the electrical properties of supercapacitors. Storage of two layers of charge is a surface process, and the characteristics of the electrode surface greatly affect cell capacitance. Carbon is the most widely used electrode material, but a lot of research is being done for metal-oxide and polymer conductor materials.

1) Carbon

Carbon has been used as an electrode material with a high surface area since the development of supercapacitors began. Until now, this is still an attractive choice because of the low cost, availability and long history of use. Carbon electrodes can be taken from a number of artificial forms such as foam, fiber, and nanotubes.

The treatment of activated carbon material affects the structure of the porosity of the electrode surface, and the accessibility of the pores to the electrolyte is very important. Ion mobility in pores is different from ion mobility in most electrolyte solutions, and is strongly influenced by pore size. If the pores are too small to facilitate access to electrolyte ions, they will not contribute to double layer capacitance. Therefore the pore size must be chosen to suit the electrolyte and thus ensure that the optimal pore size distribution is based on ion size [27]. In Figure 3.1, the effect of pore diameter on capacitance is shown, with smaller pores relatively inaccessible to ions at high frequencies.

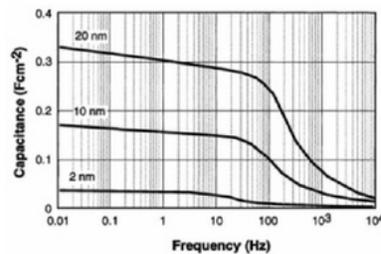


Figure 3.1 - Effect of pore diameter on specific capacitance [28].

The activated carbon material at the electrode of the supercapacitor can be made through two processes, namely carbonation and followed by activation. Pyrolysis occurs in inert gases such as nitrogen and argon. Activation is usually obtained through a process at high temperatures and involves activators such as KOH, NaOH, ZnCl₂, and H₃PO₄. The mechanism for this activation is different, with ZnCl₂ prioritizing the extraction of water molecules from the structure of lignocellulose, phosphoric acid (H₃PO₄) combining chemically the structure of the lignocellulose. The mechanism with KOH is to activate carbon that is more complex and involves the disintegration of the structure followed by the intercalation of oxygen gas from the hydroxide group [28].

Some researchers report that KOH as an activator can increase the porosity of carbon fibers, carbon nanotubes, and graphene and can improve the performance of supercapacitors but this depends on the origin of the biomass [29]. Apart from the type of activator, the particle size of activated carbon used as supercapacitor electrodes also affects the capacitance value, as in the use of carbon from palm shells as supercapacitor electrodes it is found that the smaller the particle size the more surface area and greater capacitance value such as in Table II [30].

In biomass precursor type supercapacitors, electrolyte types also greatly influence the capacitance value of the electrodes produced as reported by [31]. It was also reported that the activation method, the type of activator, the pyrolysis conditions will provide different surface area for the

activated carbon produced, and this will have an effect on the capacitance values obtained (Table III).

TABLE II. COMPARISON OF CAPACITANCE VALUES AND SPECIFIC SURFACE AREA TO THE SIZE OF OIL PALM SHELL CARBON PARTICLES

Particle size (μm)	Specific surface area (m^2/g)	Capacitance value (μF)
45	27,253	12,6976
63	15,677	3,746
90	9,356	0.041

TABLE III. COMPARISON OF ACTIVATED CARBON PRODUCED AGAINST THE TYPE OF BIOMASS PRECURSOR

Precursor Biomass	Activation method	Pyrolysis Condition	S_{BET} (m^2/g)	C_s (F/g)	Electrolyte
Banana fiber	ZnCl ₂	N ₂	686	74	1 M Na ₂ SO ₄
Banana fiber	KOH	N ₂	135	156	1 M KOH
coffee skin	ZnCl ₂	N ₂	842	156	6 M KOH
Pistacio peanut	KOH	N ₂	1009	125	HNO ₃
Rice husk	NaOH	N ₂	1886	210	3 M KCl
Tea leaf	KOH	Ar	2841	330	2 M KOH
Pine wood	Steam	O ₂	1130	142	1 M HNO ₃
Coffee bean	ZnCl ₂	N ₂	1019	368	1 M H ₂ SO ₄
coconut shell	Steam	N ₂	1532	228	6 M KOH
ginko Leather	KOH	N ₂	1775	365	6 M KOH
palm shell	KOH	O ₂	27,253	12,69	0.3 M HNO ₃
oil palm shell	NaOH	O ₂	38.10	43,792	0.3 M HNO ₃

In Table III, various types of biomass precursors provide different capacitance values, Activation methods also provide different capacitance values, such as in the treatment with carbon sources from oil palm shells, where different activators namely KOH and NaOH provide different surface areas along with the given capacitance value. In oil palm shells using NaOH activator has an effect on a larger surface area so that the capacitance value is also greater.

The conductivity of the electrode is very important for the power density of the supercapacitor. Conductivity is inversely proportional to particle size, so materials with a higher surface area and made of smaller particles will increase resistance. Power density can be increased by the use of activated carbon with larger pores, although this will limit energy storage due to reduced surface area. The use of binders also affects conductivity, and power performance is enhanced by a decrease in the percentage of binders [27].

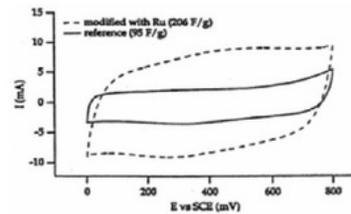


Figure 3.2 - Voltammetry plots of modified carbon electrodes [28].

The pseudocapacitive effect is often found to occur on the surface of activated carbon. The pseudocapacitance rate can be increased by carbon treatment to increase surface functionality. For example, Frackowiak [27-28] places Miller's work in which the capacitance of activated carbon is increased by the treatment of ruthenium oxide (Figure 3.2).

In addition to activated carbon, electrodes can also use materials from carbon aerogels. Airogel is a suspension of carbon nanoparticles in the gel, and has a high surface area, good conductivity, and can be used without binder. Particle size is controlled by the preparation process, and smaller particles produce larger pore surface area [27].

Nanotube offers new possibilities for carbon electrodes, but is still under study. Preliminary results indicate that higher capacitance is achieved by tangled tissue with an open central canal (Figure 3.3) [27].

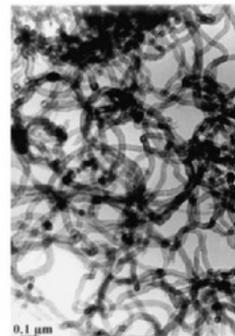


Figure 3.3 - Tangled tissue of carbon nanotubes [27].

2) Conductor Polymers

Conductor polymers store and release cargo through a redox reaction process. When oxidation occurs, ions are transferred to the polymer backbone. When reduction occurs, ions are released back into the solution (Figure 3.4). Charging in polymer film making occurs throughout the volume of film, and not only on the surface as with carbon. This offers the opportunity to reach a high level of specific capacitance.

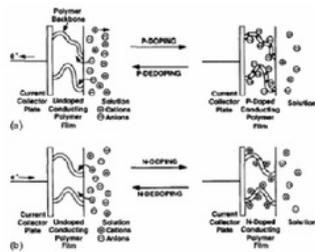


Figure 3.4 - Process of filling polymer electrode conductors [32].

Research at the Los Alamos National Laboratory [33] has produced a prototype polymer film capacitor with an energy density of 39 Wh / kg and a power density of 35 kW / kg (Fig. 3.5). The two peaks in the voltammetric plot in Figure 3.5 show that the filling process is mostly caused by a redox reaction, and only occurs in a narrow voltage range in certain cases.

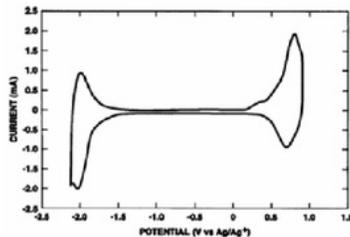


Figure 3.5 - Cyclic voltammograms of polymer films [33].

3) Metal-oxides

Metal-oxides present an attractive alternative as an electrode material due to high specific capacitance and low resistance, which can be made easier to make high-energy and high-power supercapacitors. Extensive research has been carried out on rutheniumoxides for military applications, which are expected to be cheaper than commercial ones. The US Army Research Laboratory has collected prototype cells with an energy density of 8.5 Wh/kg and a power density of 6 kW/kg [34].

Academic institutions focus on finding other cheaper materials to use than Ruthenium-oxide, but their selection is limited by the use of concentrated sulfuric acid as an electrolyte. It is believed that high capacitance and fast charging are the result of absorption of H, so that strong acids are needed to provide good proton conductivity. This reduces the choice of possible electrode material, because most metal oxides break down quickly in acidic solutions. Lighter aqueous solutions such as potassium chloride can be considered for use with metal-oxides such as manganese-oxide, and Figure 3.6 shows the profile of the prototype filling produced at Imperial College, London. The manganese oxide electrode seems to have a specific capacitance lower than ruthenium-oxide, with lower costs and lighter electrolytes may be advantageous enough to make it a viable alternative [35].

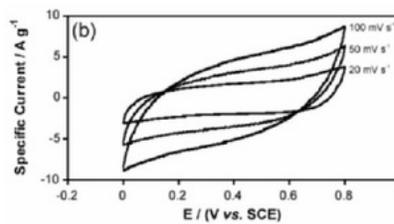


Figure 3.6 - Cyclic voltammogram for MnO films with KCl electrolytes [36].

Metal oxide electrodes can only be used with aqueous electrolytes, thus limiting the cell voltage that can be achieved. Gains in power densities with lower resistance are often offset by losses due to lower operating voltages.

3) Hybrid and Composite Configurations

The configuration of the hybrid electrode shows considerable potential, consisting of two different electrodes made of different materials. Composite electrodes consist of one type of material that is inserted into the same electrode.

In a study of polymer electrodes at the University of Bologna it was found that a high enough polymer concentration could not be realized in a negative electrode. However, positive polymer electrodes were successfully made, and activated carbon was used as a negative electrode. This hybrid configuration produces supercapacitors that outperform cells consisting of two carbon electrodes (Figure 3.7) [37]. In Figure 3.7, ▲ designate a hybrid capacitor, • indicates a carbon capacitor, and its value represents the current density in mA/cm².

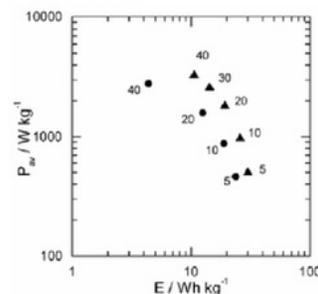


Figure 3.7 - Ragone plot of hybrid (▲) and carbon (•) supercapacitors [37].

What's interesting is the result of experiments in inserting polymers into carbon substrates to form composite electrodes. Carbon nanotubes coated with conductor polymers have produced very good results, with a high specific capacitance of 180 F/g [20, 21].

B. Electrolytes

The choice of electrolytes in supercapacitors is as important as the choice of electrode material. The cell voltage that can be achieved from the supercapacitor will depend on the breakdown voltage of the electrolyte, so that possible energy density (which depends on the voltage) will be limited by the electrolyte. Power density depends on ESR (Equivalent series resistance) cells, which are very dependent

on electrolyte conductivity. At present there are two types of electrolytes used in supercapacitor which are organic and runny.

Organic electrolytes are the most commonly used in commercial devices, because of higher dissociation stresses. Cells that use organic electrolytes can usually reach voltages in the range of 2 - 2.5 V. Organic electrolyte resistivity is relatively high, but reduces cell power. Aqueous electrolytes have a lower breakdown voltage, usually 1 V, but have better conductivity than organic electrolytes.

Supercapacitor capacitance is strongly influenced by electrolyte choice. The ability to store charge depends on the accessibility of ions to the porous surface area, so the ion size and pore size must be optimal. The best pore size distribution in the electrode depends on the size of ions in the electrolyte, so electrodes and electrolytes must be considered together.

C. Separator

Separators prevent electrical contact between the two electrodes, but are permeable ions, which allow the transfer of ion charges. Polymer or paper separators can be used with organic electrolytes, and ceramic or glass fiber separators are often used with aqueous electrolytes. For the best supercapacitor performance, the separator must have high electrical resistance, high ion conductance, and low thickness [38].

IV. FUTURE DIRECTIONS OF THE TECHNOLOGY

Supercapacitor research and technology development efforts have continued to increase since the 1970s. The pace of this progress is likely to continue because of the need for energy efficiency and increased sustainable development. Emission-free electric cars have long been the dream of many who care about environmental damage, and the potential use of supercapacitors in electric cars continues to attract attention.

The energy and power available from supercapacitors is very dependent on the material used, and significant research is directed at ways to improve the efficiency of electrodes and electrolyte materials. A good understanding of the filling process in supercapacitors can focus on important factors that must be addressed in electrode and electrolyte materials. The new method of carbon activation, polymeric materials and new metal-oxide continues to be developed, and electrolyte selection will result in an increase in cell voltage.

Supercapacitors will become more competitive energy storage options because interest in technology continues to grow and production levels increase. Awareness of the possible application and benefits of supercapacitors will gradually spread among the technical and scientific communities, and as demand continues to increase. Producers will then be able to produce cheaper devices with larger quantities.

The availability of more supercapacitors and more competitive prices along with increased energy and power will utilize supercapacitors as energy storage devices. Then the possibility of using supercapacitors will one day be the same as current batteries.

Established companies such as NEC (Nippon Electric Company) and Panasonic that have advantages in terms of

manufacturing capabilities and other commercial products will be able to support the development of new supercapacitors. New companies that do not have manufacturing capabilities may experience difficulties in providing large capital, given that the market is still relatively undeveloped. Therefore it is likely that most new companies will form joint ventures with large companies that already have manufacturing capabilities, such as those taken by PRI in a joint venture with Westinghouse [39].

V. CONCLUSIONS AND RECOMMENDATIONS

This paper aims to provide a brief overview of supercapacitor technology. Previous development efforts have been explained about current technology in a historical context. Scientific background has also been discussed to better understand the performance characteristics of supercapacitors. Armed with a basic understanding of supercapacitor performance and design problems, it is expected that readers will be better prepared to carry out design tasks in the utilization of supercapacitors as energy storage.

It is clear that supercapacitors as energy storage solutions still need a lot of attention in the early stages of development. For this reason, the evaluation of costs has not yet focused on supercapacitors as a viable alternative to batteries.

Due to the superiority of charging efficiency, long service life, fast response, and a wide operating temperature range, it is interesting to try to apply supercapacitors to any application that requires energy storage. Current technological limitations must be fully valued, and it needs to be realized that supercapacitors are only useful in a limited range of energy and power needs.

The most important thing to realize about supercapacitor technology is new and different technologies. There may be some similarities between the operation of supercapacitors and conventional capacitor operations, but there are fundamental differences from the various physical processes involved. Therefore the equivalent circuit model is a useful tool for engineers to design, and simulate so that it can provide a good estimate of how supercapacitors will behave in certain applications.

However, supercapacitors are new technologies for energy storage devices that will further encourage greater energy efficiency. Supercapacitors will be a useful tool to engineer increasingly efficient electrical and electronic systems, and as technology advances they will be increasingly useful.

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